



Gasification of biomass/high density polyethylene mixtures in a downdraft gasifier

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Abstract

In this work, an experimental study of the thermal decomposition of mixtures of wood particles and high density polyethylene in different atmospheres has been carried out in a downdraft gasifier with a nominal processing capacity of 50 kg/h. The main objective was to study the feasibility of the operation of the gasification plant using mixtures and to investigate the characteristics of the gas obtained. In order to do so, experiments with biomass only and with mixtures with up to 15% HDPE have been carried out. The main components of the gas generated are N₂ (50%), H₂ (14%), CO (9–22%) and CO₂ (7–17%) and its relatively high calorific value was adequate for using it in an internal combustion engine generator consisting of a modified diesel engine coupled with a 25 kV A alternator.

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1. Introduction

The increasing demand for energy and the consequent high consumption of natural resources has generated large quantities of residues. Sustainable development requires appropriate management of these residues, so that the associated environmental problems can be minimized. Moreover, the limited availability of energetic resources in the future has provoked a renewed interest in those technologies that allow a diversification of energy production and an energetic valorisation of residues with minimal environmental impact (Pinto et al., 2003).

In recent years, the generation of electricity from medium and small scale sources distributed in different geographical locations has received special attention as a way to increase the efficiency of energy transport. Various generation systems using biomass have been suggested as being economically competitive and environmentally friendly

ways of producing energy (Lv et al., 2004, 2007; McIlveen-Wright et al., 2006). These systems can be used in industrial and agricultural activities where residues are generated that can be converted into electricity and thermal energy by combustion or gasification. Such systems are comparatively easy to operate and with minimum emissions. Since 1998 the US Dept. of Energy has promoted the development of systems of electricity generation from biomass generating less than 5 MW for use in small communities and for industrial applications (Bain, 2002). In this context, downdraft gasification has the advantage of low tar generation, making easier the gas cleaning process for use in ignition gas engines. It is also possible to use this gas for diesel engines in dual mode for power values between 0.01 and 3 MW_{th-input} (Dornburg and Faaif, 2001). Downdraft gasifiers have generally been tested using different types of biomass such as woodchips, forest residues, rice husks, sewage sludge, etc. (Dogru et al., 2002; Wander et al., 2004; Lv et al., 2007). Their characteristics do not permit their use with powdery residues, which need to be supplied in the form of briquettes, and neither are they suitable for processing agglomerating materials due to bridges formation inside the gasifier that difficult the operation.

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The increasing volume of thermoplastic residues being generated in agricultural and industrial activities and their important energetic content has led to the study of the feasibility of co-gasification of woodchips and polyethylene. Among the gasification technologies available, probably the most suitable option for processing these mixtures would be a small scale downdraft gasifier using air as gasification agent, in order to obtain electricity. The main reason is that it generates a clean, tar-free gas at high temperatures (Dogru et al., 2002; Ponzio et al., 2006). Moreover, it is appropriate for a small processing rate, works well with a broad range of solid sizes and is relatively cheap to construct, operate and maintain. Another important advantage is that the partial combustion of the residue could enable an autothermic process to be achieved.

Some years ago a research line was initiated aiming to develop a technology for the recovery of lignocellulosic residues by using downdraft gasifiers and air as gasification agent (Usón, 1999). In the present work, an experimental study has been carried out consisting of the gasification of woodchips and polyethylene in a downdraft gasifier with a nominal capacity of 50 kg/h. The main goal is the study of the gasification potential of this type of mixture and to determine the influence of the operating conditions on the flow rate and quality of the products obtained. The addition of plastic is expected to increase considerably the calorific content of the gas obtained.

2. Methods

2.1. Gasification pilot plant

Gasification tests were performed in a downdraft gasifier/IC engine power plant, already described in previous works (Usón, 1999) and shown in Fig. 1. This basically consists of a downdraft gasifier, feeding systems of wastes and air, an ash removal system, gas conditioning systems, control and measurement systems, a start-up system and an IC engine generator of 25 kW A. The nominal processing capacity is 50 kg/h. The solid feeding system comprises

a belt conveyor, two hoppers, a cylindrical compartment and two pneumatic gate valves. The waste is fed into the gasifier in a pseudo-continuous way: The solid level inside the gasifier is kept constant by means of a rotating-paddle level sensor. When the material level falls below a set point the feeding system is switched on. The air feeding system includes a Roots blower, a rotameter and a ring with three injectors with a radial distribution located in the throat zone, supplying air into the gasifier.

The gasifier is a cylindrical reactor with an inside diameter of 0.44 m, a bed height of 2 m and a throat diameter of 0.35 m. The solid bed rests on a perforated eccentric rotating grate at the bottom of the gasifier. Once the product gas leaves the gasifier, it is conveyed through a cleaning and cooling system. The gas flows through a cyclone, two wet scrubbers (to remove the dust and tars), an air–gas heat exchanger, and a gas–water shell and tube heat exchanger (to condense the gas moisture). The gas is subsequently conditioned for use in an internal combustion engine. A power generation unit is installed at the end of the gas pipe in order to analyse the combustion performance of the gas produced for power generation. This unit consists of a modified diesel engine coupled with a 25 kW A alternator. The energy generated is used in an electric resistor set for air heating. A general control and data acquisition system developed by the Scientific Instrument Service at the University of Zaragoza is incorporated into the plant, allowing on-line modification of the operating conditions and an automated control of the installation.

2.2. Gas measuring system

The gasification plant is equipped with two on-line gas analysers as well as a gas chromatograph. An infrared analyser (Fisher Rosemont, Model BINOS 100) allows the continuous monitoring of CO and CO₂. A paramagnetic analyser (Fuji Electric, Model ZAJ) quantifies the oxygen content in the gas sample. The gas composition (CO, CO₂, H₂, N₂, CH₄, C₂H₂, C₂H₄ and C₂H₆) is analysed by a gas chromatograph (Hewlett Packard, Model

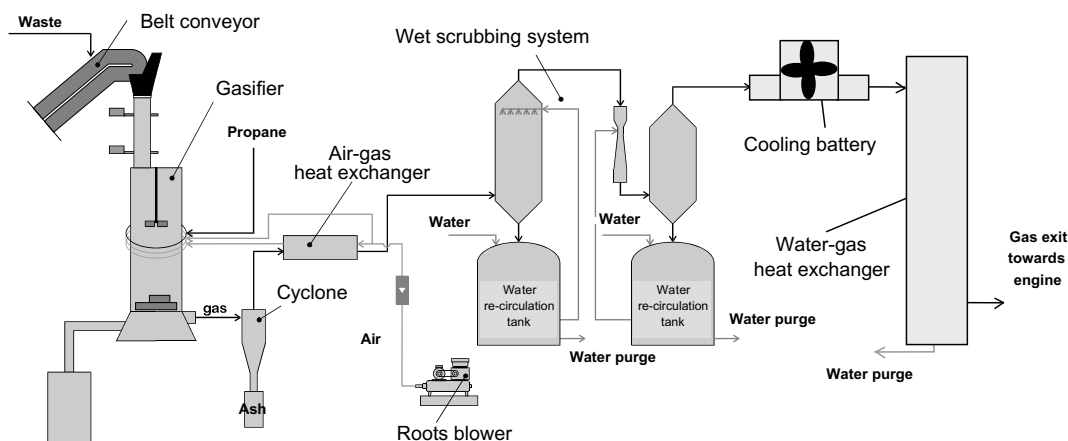


Fig. 1. Plant schematics.

5890 series II) with a Porapak N column and a molecular sieve. The equipment uses a TCD detector and helium as carrier gas.

2.3. Experimental procedure

Each test starts with the checking of the bed level inside the reactor. Air and propane are supplied into the gasifier and the burner switches triggered by the start-up system. When the throat temperature reaches 500 °C, the start-up system is turned off. The air flow-rate and the moving frequencies of the different mechanical devices (grate, agitator and screw conveyor) are then selected. It is considered that steady-state has been reached in an experiment when the temperatures in both the oxidation zone and the reduction zone are approximately constant. The gas sampling valve is then opened. When the experiment finishes the gas sampling valve is closed, the feeding system and the ash removal system are turned off and the air flow-rate is stopped. A low flow rate is used for the air supplied through the burners until the throat temperature is below 500 °C.

2.4. Properties of studied residues

The experiments were carried out using mixtures of biomass and polyethylene (HDPE). Wood was supplied in the form of chips with an approximate size of 40 × 40 × 50 mm. HDPE was supplied as chips of 5 × 5 × 2 mm approximately. The ultimate analysis of the wood was carried out by means of a multi-element analyser (Carlo Erba 1108). The water content was determined following standard ISO 589:1983 (ISO, 1983). Volatile and ash contents were obtained in accordance with standards ISO 562 (ISO, 1998) and ISO 1171:1997 (ISO, 1997), respectively. For the determination of the calorific content, ISO 1928:1995 (ISO, 1995) was used. The HDPE can be considered water and ash free, and the ultimate analysis corresponds to the unit $-\text{[CH}_2\text{]}-$. The main characteristics of the materials are shown in Table 1.

Table 1
Characteristics of residues

Analysis	Wood	HDPE
<i>Proximate (wt%)</i>		
Moisture	29.0	—
Volatile matter	60.76	100
Fixed carbon	9.92	—
Ash	0.32	—
<i>Ultimate (wt% db)</i>		
Carbon	35.12	85.71
Hydrogen	7.57	14.29
Oxygen	56.96	—
Nitrogen	—	—
Sulphur	0.03	—
<i>L.H.V. (MJ/kg dm)</i>	17.81	44.0
<i>Bulk density (kg/m³)</i>	451	442

db: dry basis, dm: dry matter.

2.5. Gasification tests

In order to check the processing rate of the two materials, the percentage of polyethylene supplied in the feed and the air flow rate have been varied. The variation of the air flow rate enables the system to reach stationary conditions, characterized by constant reactor temperatures and composition of the produced gas. The feed consumption is determined at the end of each run and depends basically on the air flow rate supplied. Actually, this is the only operation variable that can be modified. The air flow introduced into the reactor determines the bed temperatures and thus, the reaction rate and as a consequence the solid feeding rate.

For the determination of the element balances, the material consumption is determined at the end of each experiment as it has been previously mentioned and the air flow rate is measured. From this value and the composition of the gas generated, a nitrogen balance can be set to determine the flow rate of gas generated. From this value, the ultimate analysis of the material, its flow rate and the composition of the gas generated, the balances for the rest of elements can be set and solved. For the analysis of the results, the following relationships have been applied:

- Equivalence ratio (ER), defined as the ratio between the air flow rate supplied and the stoichiometric flow rate necessary for complete combustion. The values of this parameter for the different experiments carried out are approximately constant (0.3–0.4).
- CGE, the ratio of chemical energy in the gas and chemical energy in the fuel.

The operating conditions used in the different experiments are shown in Table 2. The experiments are grouped (P1, P2 and P3) according to the percentage (wt.) of HDPE in the material fed. In each group, the air flow rate is varied. Given the complexity of the experimental system used in this work, several previous tests have been carried out in order to check the correct performance of the whole plant. For each experiment specified in Table 2 at least three previous tests have been performed until the behaviour is considered adequate for obtaining a good reproducibility of the results. The composition of the gas obtained expressed in percentage volume (dry basis), the calorific content and the CGE are also shown in Table 2. The compositions shown are average values of the results obtained from different samples taken throughout the experiment. The calorific content has been calculated from the average composition of the gas.

3. Results and discussion

The feed consumption (biomass/HDPE) vs. air flow rate for different HDPE percentages is shown in Fig. 2. As can be observed, the consumption increases as the air flow rate increases when woodchips or mixtures with 10% of HDPE

Table 2

Experimental conditions, product gas composition (vol%), L.H.V and C.G.E. "C2" includes C₂H₂, C₂H₄, C₂H₆

Run	Q_{air} (Nm ³ /h)	Feed (kg/h)	HDPE (wt%)	Q_{gas} (Nm ³ /h)	H ₂	O ₂	N ₂	CH ₄	CO	CO ₂	C ₂	L.H.V. (MJ/Nm ³)	C.G.E. (%)
P1-1	43.0	34.4	0.0	56.8	11.2	0.5	59.3	0.8	10.1	17.3	0.7	3.2	44.5
P1-2	50.0	40.4	0.0	66.9	15.1	0.7	57.4	0.9	10.2	14.7	0.9	3.7	48.5
P1-3	60.0	46.0	0.0	82.4	14.8	0.4	56.0	1.2	9.4	17.2	1.1	3.8	52.1
P2-1	38.7	29.6	9.6	59.5	13.9	0.3	50.9	2.0	19.2	12.0	0.8	5.6	66.3
P2-2	51.9	35.3	9.8	80.3	13.7	0.5	50.5	2.5	20.1	10.6	1.2	6.1	81.9
P2-3	59.3	37.9	9.5	94.3	15.1	0.4	49.2	2.4	20.2	10.8	0.9	6.1	90.2
P3-1	40.0	33.4	15.2	61.9	14.4	0.1	50.4	3.1	19.6	9.6	1.7	6.7	65.9
P3-2	52.5	30.9	17.4	81.5	14.6	0.6	50.8	3.0	22.5	7.3	1.6	6.9	93.6

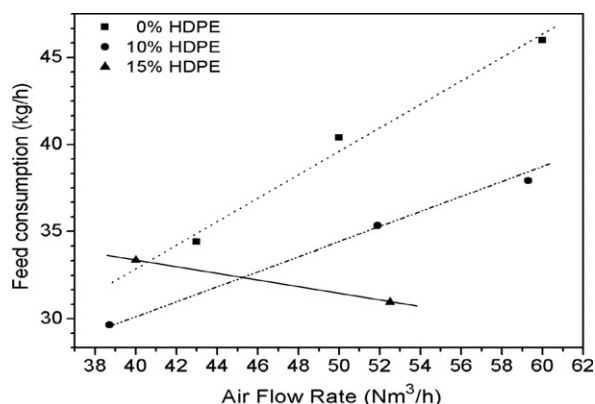


Fig. 2. Consumption of residue vs. air flow rate for different %HDPE.

are fed, this increase being more significant in the latter case. When the HDPE content is 15–17%, the behaviour is not clear. The solid consumption in the gasification unit is obviously determined by the residence time of the solid. The different behaviour of wood and HDPE during their degradation influences the residence time. During pyrolysis the size of the wood particles decreases only slightly whilst HDPE particles melt and vaporize rapidly without generating solid residues. The solid does not leave the gasifier until the particles are small enough to pass through the orifices of the rotating grate at the bottom of the gasifier. In fact, this makes that the residence time and thus, the solid feeding rate depends on the conversion rate of wood. Taking this into account, the carbon content remaining in the ashes is negligible. The shorter the time necessary to reach a specific size, the greater the consumption. Since HDPE is more reactive than wood, the polymer decomposes rapidly at approximately 400 °C to generate volatile hydrocarbons, resulting in a high consumption of oxygen, higher temperatures in the oxidation zone and thus in the drying and reduction zones.

When the polyethylene content is 10%, the gasifier temperature increases, but the remaining oxygen concentration is high enough to oxidize gases and tars from the pyrolysis of wood. This in turn favours the conversion of char in the reduction zone. As the air flow rate increases, the feeding rate increases. As has been stated above, this influence is less significant when a mixture containing 10% of HDPE rather than only woodchips is fed. For the highest HDPE

content studied (15–17%), the temperature in the gasification unit increases, although the available oxygen (coming from the pyrolysis zone) for the partial combustion of the char is less. Under these conditions, the wood conversion is lower and the size of char particle bigger, the rate of extraction is lower than the previous one, and thus, the feed rate is lower for a given air flow rate. As a consequence, the residence time of the biomass in the reduction zone increases and the conversion of fixed carbon increases, so that the production of CO increases. The efficiency of the process increases too, as has been corroborated by the tests performed.

From the experimental results obtained (shown in Table 2), it can be observed that the flow rate of the gas generated (Nm³/h) increases linearly as the air flow rate supplied increases, both in wood-only and in wood/HDPE runs. The gas production is higher when using HDPE, and shows a linear relationship with the air flow rate identical to that appearing when using biomass only. When studying the results of the gas yield obtained vs. the feed rate for different HDPE percentages, it can be observed that the gas volume per kg of feed increases as the percentage of HDPE increases from 0% to 10%. This parameter also increases as the air flow rate does. Although the flow rate of gas produced is similar for the two HDPE contents, the gas yield will be higher for a higher content of HDPE.

The gas composition determines its calorific content. Whilst in biomass gasification the main combustible components are CO, H₂ and CH₄, in polymer gasification a significant amount of other hydrocarbons can appear. The analysis of the results obtained (shown in Table 2) indicates that the H₂ concentration varies only slightly with the HDPE content and air flow rate, whilst the CH₄ and C₂H₄ concentrations increase as HDPE content increases. The air flow rate does not seem to have a significant influence on the concentration of the other HCs (C₂H₂ and C₂H₆).

Berrueto et al. (2004) carried out gasification experiments with mixtures of pine sawdust and HDPE in a fluidized bed, studying the influence of the temperature on the composition of the gas obtained, using an ER of 0.06 and a HDPE/biomass ratio of 1.5. The results obtained show similar trends to those obtained in the present work, taking into account the differences in the experimental systems and the plastic/biomass ratio. In both cases the gas

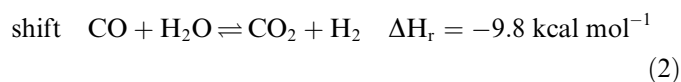
obtained shows a higher content of hydrocarbons due to the presence of polyethylene, higher yields of H_2 and an increase in the CO/CO_2 ratio as the temperature increases.

As regards the production of CH_4 , the results presented here are consistent with those obtained by other authors (Na et al., 2003; Pinto et al., 2002). The concentration of CH_4 increases as the HDPE content increases due to the HDPE cracking, not to the metanation reaction. Regarding the CO and CO_2 concentrations, the value of the CO concentration obtained in biomass experiments is approximately half the value obtained in the mixture experiments with 10% HDPE as can be observed in Table 2. As the HDPE content and the air flow rate increase, CO generation increases and CO_2 decreases. The CO/CO_2 ratio varies only slightly between 0.54 and 0.69 in the biomass-only experiments. With 10% HDPE, CO/CO_2 ratio shows values from 1.6 up to 1.89 and a slight increase is observed and with 15% HDPE a clear decrease is observed when the feed rate increases. This CO/CO_2 ratio strongly influences the calorific content of the gas: as the ratio increases, the calorific content increases.

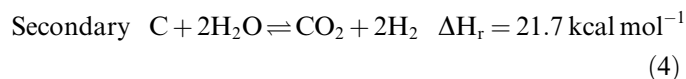
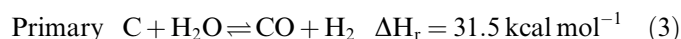
Some authors (Pinto et al., 2002) suggest that HDPE favours the Boudouard reaction against the water gas shift reaction, due to a higher concentration of C or HC radicals generated during cracking.



Water-gas



Water gas:



It should be noted that no water steam is fed to the gasifier. The water content in the biomass, released in the drying zone of the gasifier is consumed in the water gas reactions.

An increase in the air supplied favours the combustion reactions, and increases the temperature. As can be observed in Table 3, temperatures in all the zones increase

as the air flow rate and the HDPE supplied increase. In experiment P3-2 the temperature in the oxidation zone should be higher than the value of 1092 °C measured, since the pyrolysis and reduction zones show an increasing trend. However, this value is lower than that of experiment P3-1.

It would be expected that the CO_2 concentration would increase with an increase in the equivalence ratio, but there are various other factors influencing CO and CO_2 distribution such as the higher reactivity of the char as the temperature increases, the existence of reduction conditions due to HDPE cracking or the partial reaction of oxygen with the tars produced in the process. As the reduction zone temperature increases, so does the reactivity of the residue so that higher conversions are obtained. This is corroborated by the results obtained that can be observed in Fig. 3, where the concentrations of CO and CO_2 are plotted versus the hydrocarbon concentration (HC). CO_2 formed in the initial combustion zone will react with char or with hydrocarbon radicals, increasing the CO concentration.

As the temperature increases, the relative importance of the water gas reaction will be greater than that of the water gas shift reaction, although the hydrogen concentration remains practically constant when varying both the air flow rate and HDPE content. This indicates that the contribution of these reactions is less important than that of the Boudouard under the conditions studied. The calorific content

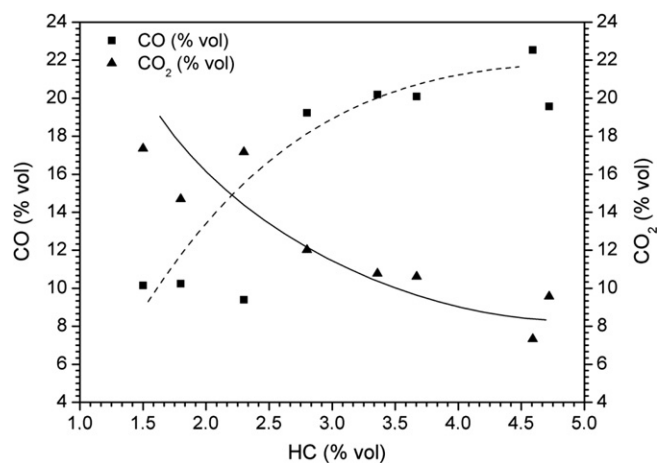


Fig. 3. CO and CO_2 evolution vs. hydrocarbon concentration (vol%).

Table 3
Gasifier temperatures of the different runs

Gasifier					Air blower (°C)
Zone	Drying (°C)	Pyrolysis (°C)	Oxidation (°C)	Reduction (°C)	
P1-1	102	221	1076	787	75
P1-2	91	295	1244	687	70
P1-3	103	231	1460	687	113
P2-1	110	214	1304	620	85
P2-2	106	289	1532	806	116
P2-3	113	353	1617	957	139
P3-1	109	247	1256	779	109
P3-2	122	361	1092	811	126

of the gas obtained in the different experiments is shown in Table 2. It can be observed that the lower heating value increases with the feed rate due to an increase in the gasification temperature and conversion, resulting in a gas with a higher concentration of combustible compounds.

A sharp increase in the lower heating value is observed when increasing the HDPE content of the feed. The value corresponding to biomass-only gasification is only half that obtained when gasifying a mixture with 10% HDPE, due mainly to the fact that the CO concentration is doubled. The slight difference observed between the values corresponding to 10% and 15% HDPE can be explained by the higher concentration of CH₄, C₂H₆, C₂H₄ and C₂H₂. The lower heating values obtained by several other authors (Berrueco et al., 2004; Na et al., 2003; Pinto et al., 2002) are higher than those presented here, between 6 and 20 MJ/Nm³, due to a higher HDPE/biomass ratio. Pinto et al. (2002) found that an increase in HDPE leads to a higher calorific content of the gas over the whole range of vapour/residue ratios, as well as higher energetic conversions, which is consistent with the data presented here.

The CGE parameter, also shown in Table 2, indicates the energetic efficiency of the process. This parameter increases proportionally and linearly as the air flow rate increases. It also increases as the HDPE content in the feed increases. This increase is a result of the higher energetic content of the gas due to the hydrocarbon presence. It can also be observed that the CGE value increases more significantly when the HDPE content is raised from 0% to 10% than from 10% to 15%. Two facts can explain this behaviour: with 15% HDPE, the hydrocarbon concentration in the gas increases, to a lesser extent than with 10% HDPE, and the energy of the combustible also increases due to the increase in the plastic content. However, these CGE values should be treated with caution and considered only as indicative of trends. An explanation of these results can be found by analysing the material balances, as observed in Table 4. Whilst the oxygen balance is almost closed in every case (higher than 90%), values higher than 100% (up to 119%) have been obtained for carbon in the tests done with the highest flow rates and plastic contents. During the experiments, the stationary state is apparently reached when constant values are achieved for the temperature, flow rate and gas composition but not yet for the

solid rate. As has been mentioned, the temperature increases as the HDPE content increases, so the reduction reactions of the char are favoured, increasing the consumption of the char, and explaining the high energetic efficiency values.

4. Conclusions

The main conclusions that can be established from this work are as follows:

- Mixtures of biomass and HDPE can effectively be gasified in a downdraft gasifier. The biomass acts as a bed, and allows the feeding of polyethylene into a system that would not otherwise admit powdery or agglomerating materials.
- The operational problems detected are related to the gas production, which causes an increase in the pressure drop in the cleaning and conditioning system, and which limits the HDPE content to a maximum of 17%, avoiding the use of higher air flow rates.
- Polyethylene causes an increase in the temperatures in the gasification unit, increasing the biomass conversion and the energetic yield since reduction reactions are favoured. This means that the CO/CO₂ ratio increases as the HDPE content in the feed increases.
- The gas obtained has a stable composition, an increasing heating value as the HDPE content increases and, to a lesser extent, as the air flow rate increases. The highest values are obtained for ER of 40%. The gas obtained is suitable for use in dual diesel engines.

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Table 4
Element balances (%)

Run	C	H	O
P1-1	78	77	90
P1-2	82	87	90
P1-3	92	93	92
P2-1	94	80	98
P2-2	108	89	97
P2-3	119	85	92
P3-1	83	80	90
P3-2	115	91	94

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